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ScienceDirect

Energy Procedia 38 (2013) 404 – 409

Energy Procedia

SiliconPV: March 25-27, 2013, Hamelin, Germany

Improvement of PV cell efficiency by rectifying antenna

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Abstract

Solar cells built from single-crystalline silicon, as alternative energy sources, became the most widely used in recent years. The main stream manufacturing approach is to process silicon solar cells from Si wafers, and then assemble these cells into photovoltaic modules. However, a significant portion of solar energy, corresponding to the infrared radiation with wavelength in the range 1-3 μm, is lost. According to the known solar spectrum, the solar energy coming to Earth in the diapason of 1-3 μm equals to ~ 216 W/m^2. In this work, we present an investigation of a new system which is capable of utilizing the radiation energy in this frequency band.

This novel converting system is based on rectification of the very high frequency radiation with a nano-dimensional antenna and rectification with a metal-insulator-metal thin film system. This system represents a tunneling diode, made of metals with various work-functions separated by a thin dielectric layer. To test the efficiency of this novel converter and the choice of parameters of thin films we used a computer modeling of the system. Modeling and simulation were performed using PSpice.

It was shown that a short circuit current may reach the value of 46.2 nA and the open circuit voltage can reach 4.62 mV for a single antenna. It was found that the optimum load resistance equals to 175-200 Ω, which provides a maximum generated power of 35 fW for a single antenna. Efficiency of the loaded system reaches up to 16.33%.

Keywords: Silicon solar cells, Rectifying antenna, Efficiency

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Selection and/or peer-review under responsibility of the scientific committee of the SiliconPV 2013 conference
doi:10.1016/j.egypro.2013.07.296

1. Introduction

The sun sends to earth a lot of energy. All this energy is distributed in a narrow range of wavelengths. We convert light energy into electricity using the photovoltaic effect, but a significant part of that energy is lost due to restrictions caused by the nature of semiconductors we use. Solar cells based on the photovoltaic effect, utilize only photons with energy higher than the bandgap of the used semiconductor. Thus, for silicon solar cells, a significant part of the solar energy, more than 20%, corresponds to the near infrared radiation with wavelength in the range of 1-3 μm, is lost. According to the known solar spectrum, the solar energy coming to Earth in the diapason of 1-3 μm equals to ~ 216 W/m^2 [1]. Fig. 1 represents the spectral distribution of the incoming solar energy. Estimation shows that we can obtain approximately 4.62 mV from each nanometer of incoming energy.

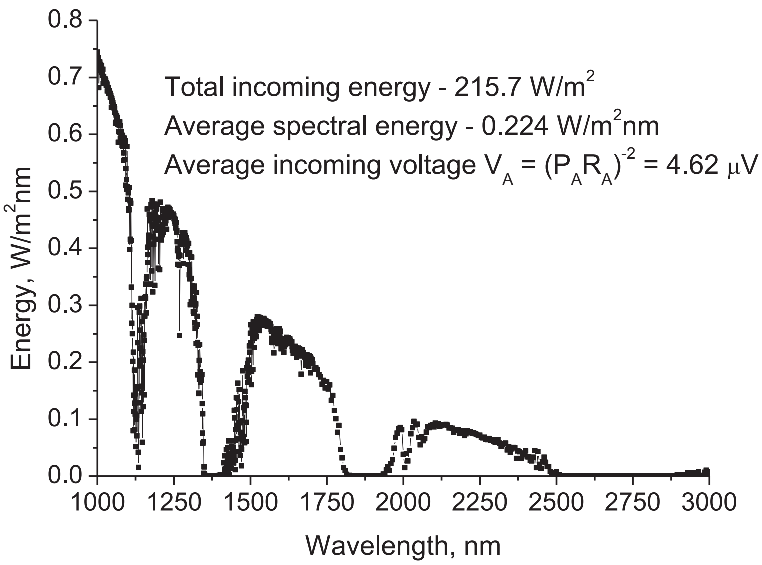

Fig. 1. Spectral distribution of the incoming solar energy.

An alternative way to use this energy is to absorb it using nano-dimensional antenna. Energy that cannot be converted into electricity using photovoltaic effect may be absorbed and successfully converted to electricity using a Metal-Insulator-Metal (MIM) thin film system representing a novel nano-dimensional antenna based on a MIM rectifying diode. Such diode is capable to switch in a very short time of 10^{-15}-10^{-16} sec. Thus, this converter consists of an antenna integrated with a MIM rectifying diode and a low pass filter.

2. Type, shape, and materials used for the rectifying system

For radiation energy harvesting we have chosen a half-wavelength dipole antenna with the central feed point which can transmit and receive electromagnetic radiation of a wide range [2]. In our case, the field of interest is a wide spectrum in the range of 100 - 300 THz with a feed point in 200 THz. This frequency relates to the wavelength of 2 μm and energy of an electro-magnetic wave of approximately 0.6 eV.

The MIM thin film system which we used in our investigation was Al–Al_2O_3–Au (Aluminum-Aluminum Oxide-Gold). These metals, Al and Au, are chosen due to convenient difference in the work functions of metals closed to 0.6 eV. Both metals aluminum and gold can be deposited in vacuum using reliable vacuum deposition systems, for example thermal evaporation or sputtering. Thin insulating film Al_2O_3 is a native oxide which grows on the aluminum surface. Thickness of this oxide film is 2-4 nm and does not exceed 5 nm [3, 4]. The aluminum oxide film is continuous, dense and has a good adhesion to the Al metal surface. Fig. 2 represents a principle scheme of the rectifying antenna.

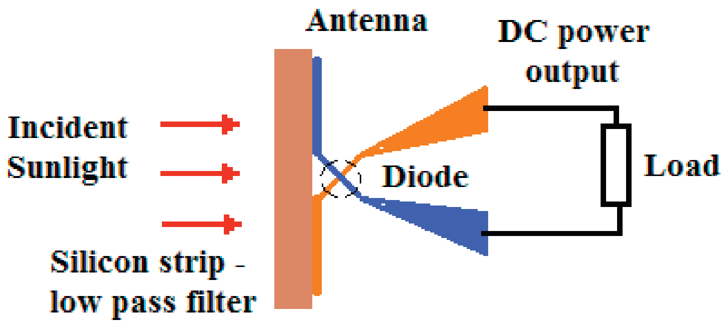

Fig. 2. Principle scheme of the rectifying system.

As shown in Fig. 2, the system of rectifying antennas should be arranged on the rear side of a PV solar cell. In this case, the silicon plate will play a role of a low-pass filter; all energy with wavelength higher than the red edge of the silicon, 1.08 μm, and transmitted through it, will be used for conversion in the rectifying antennas system.

Our half-wavelength dipole antenna represents two metal bands with the length of 0.5 μm and width of 0.22 μm. The internal antenna's resistance was chosen as 100 Ω. The MIM diode has a rectangular shape with area of ~0.05 μm^2. Probability of tunneling between these metals through oxide film depends on the potential barrier height, energy of excited electrons and the dielectric film thickness, as in the following [5]:

$$D = exp\left\{-2d\left[\frac{2m(\Phi_B - E)}{h^2}\right]^{0.5}\right\} \tag{1}$$

Where d is the thickness of the dielectric layer, $\Phi_B = \Phi_{Au} - \Phi_{Al}$ is the potential barrier height, m and E are mass and energy of electrons. Generated voltage in this case can be represented by the sum of the DC voltage produced by the difference of work functions of the selected metals and by energy of coming photons which depends on the solar light wavelength. Capacity of the antenna was defined by the MIM diode area and the Al_2O_3 layer thickness, C_D = 7.95 aF.

3. Simulation of the rectifying antenna

To check the efficiency of rectifying antenna as a radiation energy converter, we applied a computer modeling for the system using PSPICE software. For the simulation we had chosen a model of H. Odashima et al. [2]. The equivalent circuit diagram of the system consists of three parts. First part is an antenna represented by the voltage generator and a serial or internal resistance R_A. The second part is a

MIM diode represented with the junction capacity C_D, a contact resistance R_S and the tunneling resistance R_T depending on the frequency of absorbed light. The third part is a load consisting of resistance R_L and capacity C_L. Fig. 3 represents an equivalent scheme of the system.

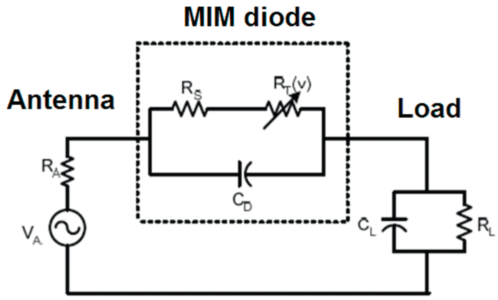

Fig. 3. An equivalent circuit diagram of the rectifying system.

If we denote the ratio of the voltage at the load to the voltage of the antenna as an efficiency of rectification, $\eta_V = V_L/V_A$, the average current through the load and the antenna's voltage can be expressed as functions of this parameter:

$$I_M = \frac{V_A^2}{2\pi R_0}\left[\left(1+\frac{2V_L^2}{V_A}\right)arccos\left(\eta_V\right)-3\eta_V\sqrt{1-\eta_V^2}\right] \tag{2}$$

$$V_A = \frac{2\pi R_0 \eta_V}{R_L\left(1+2\eta_V^2\right)arccos\left(\eta_V\right)-3R_L\eta_V\sqrt{1-\eta_V^2}} \tag{3}$$

Here $R_0 = R_S + R_T$ and $V_L = R_L \cdot I_M$. These functions were used in our simulation experiments.

Simulation was provided for various load resistances 10-1000 Ω for a single antenna and for different systems using serial and parallel connection of single antennas. Evidently, the power produced by individual antenna is very small. Real systems have to be a complex configuration of individual antennas, providing the necessary voltage and current to the load. The required power is provided by a combination of serial and parallel connection of individual antennas [7].

Fig. 4 represents a current-voltage characteristic obtained for various load resistances as a result of the simulation. Also, the figure shows the power output for a single antenna as a function of load resistance. As shown, a short circuit current may reach the value of 46.2 nA and the open circuit voltage can reach 4.62 μV for a single antenna. It was found that the optimum load resistance equals to 175-200 Ω, which provides a maximum generated power of 35 fW for the single antenna. Efficiency of the system with open circuits may reach 89.6% (this was measured for high load resistance of 1000 Ω). Efficiency of the loaded single antenna's system, estimated as the relation between the rectified power P_{DC} and the incident power P_{IN}, reaches up to 16.33% for the system loaded by an optimal load.

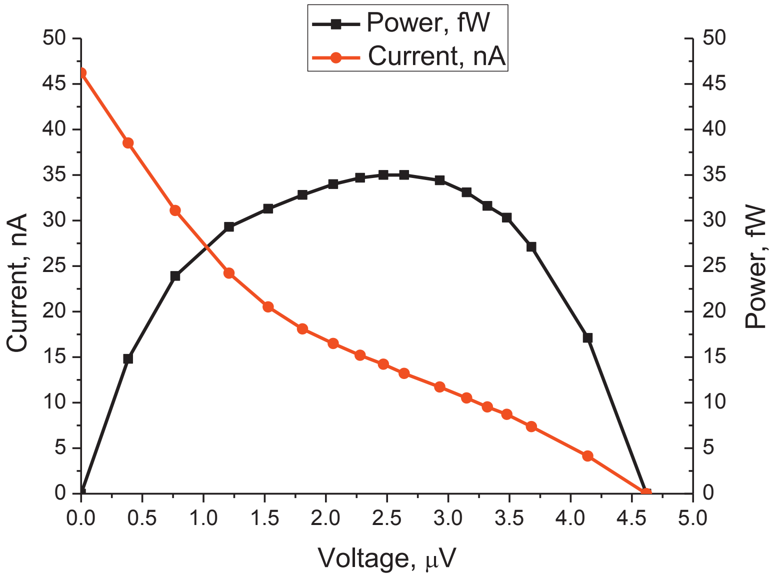

Fig. 4. Current-voltage and power characteristics of the rectenna obtained by simulation.

To check possibility of serial and parallel connections of rectifying antennas we carried out simulations of such systems, which include 10 separate elements.

In these simulations we calculated the load resistance according to follows formulations:

$$R_L = R_0 + R_1 + ... + R_9 = 2000\ \Omega \text{ for the serial connection} \tag{4}$$

And

$$R_L = \left(\frac{1}{R_0} + \frac{1}{R_1} + ... + \frac{1}{R_9} \right) = 20\ \Omega \text{ for the parallel connection} \tag{5}$$

We obtained the following results:

- The serial connection: the system current was 13.22 nA and the total voltage was 26.4 μV.
- The parallel connection: the system current was 132.2 nA and the total voltage was 2.64 μV.

Evidently, each connection method has its advantages and disadvantages. The serial connection enables to increase the load of the system. In turn, the parallel connection provides independent behavior of antennas connected in the system, which increases the reliability of the system.

4. Conclusions

The simulation showed good agreement with the theory. As shown, a short circuit current may reach the value of 46.2 nA and the open circuit voltage can reach 4.62 mV for a single antenna. It was found that the optimum load resistance equals to 175-200 Ω, which provides a maximum generated power of 35 fW for the single antenna. Efficiency of the system with open circuits may reach 89.6% (this was obtained for high load resistance of 1000 Ω). Efficiency of the loaded system reaches up to 16.33%. Efficiency of the system may be increased through creation of rectifying bridges based on MIM diodes.

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